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Research papers

Climatic anomaly and its impact on vegetation phenology, carbon sequestration and water-use efficiency at a humid temperate forest

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ABSTRACT

Changing climate, especially extreme weather event, is exerting considerable impacts on the hydrological and biogeochemical processes in forests worldwide. A deep understanding of climate change–terrestrial feedbacks is essential to predict future regional/global carbon and water budgets, which can be used to develop potential strategies for forest management. In this study, totally 11 years of eddy covariance tower measurements of CO_2 and H_2O fluxes, as well as the relevant environmental variables were analyzed to reveal the effects of climate anomalies on vegetation phenology, carbon sequestration and ecosystem water-use efficiency (WUE) dynamics in a humid temperate deciduous forest. Warmer spring temperatures altered the phenological phases with the green-up date advanced approximately 3.5 days per °C, and the extended growing season of about 3 days per °C, reaching the peak in 2012. Because of spring temperature anomaly, the shift from carbon source to sink occurred nearly 40 days earlier than usual. But the abnormal carbon dynamics happened during the peak growth period. Correlation analyses indicated that the amount of precipitation dominantly controlled the capacity of forest carbon sequestration (NEP) in this area. Therefore, the subsequent water scarcity owing to the extremely dry summer together with heatwave severely decreased the forest NEP by about 64.1%. Further analyses implied that the sharp reduction in gross primary production (GPP) rather than ecosystem respiration (Re) resulted to the decrease in NEP. Both GPP and evatranspiration (ET) were larger during the springtime in 2012 than those at adjacent years. But severe summer drought reduced the ecosystem WUE and yielded the lowest GPP and ET. Further work must focus on improving the recognition of forest feedback to climate systems.

1. Introduction

Global climate change has significantly affected ecosystem functions and processes, including tightly coupled terrestrial carbon and water cycles (Mu et al., 2011; Keenan et al., 2013; Yang et al., 2015). The potential consequences resulting from climate anomalies particularly extreme weather events such as floods, droughts and heatwaves were considered more severe (IPCC 2007, 2012; Tang et al., 2017). Drought is generally defined as a prolonged period of months or years when precipitation is apparently less than the multi-year average, resulting in water scarcity for ecosystem health and food security (Thenkabail et al., 2012; Wilhite, 2016). In addition, drought is a natural disaster that causes the most severe economic and social losses (Carrao et al., 2016). The frequency and intensity of droughts have increased across a wide range of spatial scales in recent decades (Trumbore et al., 2015). Thus, understanding the responses of forest ecosystem to climate extremes is critical, considering that future drought will become more intense than those experienced in the past century.

Vegetation phenology, which directly impacts the dynamic balance of terrestrial carbon budget and exerts feedbacks to climate system, is receiving more and more attention in recent years (Richardson et al., 2013). Studies on vegetation phenology are vital in understanding the changing trend of natural seasonal phenomena and can serve as guide for global agricultural production and ecological change (Olmstead and Rhode, 2011; Yu et al., 2017). In addition, changes in vegetation phenology are key indicators of the response of terrestrial biosphere to

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climate change through variability in the carbon, water and energy cycles (Tang et al., 2014; Morison et al, 2015). Phenological information, including the start and end dates of the vegetation growing season (SOS and EOS), is crucial to evaluate ecosystem responses to climate change because of its high sensitivity to climate (particularly temperature) and extensive influence on ecological processes (Forrest and Miller-Rushing, 2010; Anwar et al., 2015; Cong et al., 2017). Zaitchik et al. (2006) proposed that an early green-up in spring 2003 could be due to anomalous warm temperatures, and recent studies revealed the EOS delay greatly contributed extension of the growing season (Wu et al., 2013; Garonna et al., 2016). Nonetheless, the effects of climatic anomalies considerably vary because of various forest communities under different climate zones.

Carbon sequestration of forests is severely affected by interannual variation in climate factors, and the magnitude could be sharply reduced by extreme weather events and human disturbances (Ciais et al., 2005; Niu et al., 2011a; Tang et al., 2017). Thus, understanding the responses of net ecosystem CO_2 exchange (NEE) to such events is central to clarify the climatic anomaly-carbon cycle feebacks, and determine the underlying processes and mechanisms across forests. In addition to the unpredictability of climate change, plenty of uncertainties existed regarding the future trend and strength of terrestrial carbon sink (Reichstein et al., 2013; Sitch et al., 2015; Mystakidis et al., 2016). It is mainly dominated by high interannual variability in both ecosystem gross primary productivity (GPP) and ecosystem respiration (Re) components facing climate change at regional to global scales (Ahlstrom et al., 2015; Mekonnen et al., 2017). Many attempts have to be made for exploring the interactions between climate extremes and temperate or boreal forests as the most likely explanation of the missing carbon sink on Earth.

Water use efficiency (WUE) refers to the amount of carbon gained per unit of water consumed in terrestrial ecosystems. Understanding its dynamics and the associated environmental controls is essential for tracking ecosystem responses to future climate changes (Niu et al., 2011b; Tang et al., 2014; Huang et al., 2015). Meanwhile, ecosystem WUE provides information on biological and physical processes of ecosystems, which can enhance our ability to understand the interactions between ecosystem productivity and water availability (Beer et al., 2009; He et al., 2017). Given the warming-associated acceleration of terrestrial water cycle (Trenberth and Asrar, 2014), monitoring and evaluating the changes in ecosystem WUE under varied hydroclimatic conditions are crucial for understanding the response of ecosystem functions (e.g., sensitivity, adaption, and resilience) to climate change, particularly extreme weather condition (Zhou et al., 2017).

Actually, all these ecosystem functions are closely related to the climatic change, whereas few attempts have been made to disclose the interactions among them in-depth. Once the climatic anomalies happened, it would directly affect the vegetation phenology. Then, the changed photosynthesis and ecosystem respiration will obviously alter the carbon sequestration capacity in conjunction with ecosystem water-use efficiency. Therefore, 11 years of flux tower measurements of carbon and water exchanges, and the relevant environmental variables at a temperate deciduous forest were analyzed in this study. The work addressed to i) examine the impact of spring temperature anomaly on vegetation phenology including SOS and the length of the growing season (LOS); ii) reveal the interannual and seasonal variabilities in NEE and its component fluxes, GPP and Re during the periods of varied climate anomalies; and iii) identify the responses of ecosystem WUE to such events encompassing warm spring and extremely dry summer. All analyses will expand our understanding and predictions of the effects of global climate change on ecosystem functions and processes.

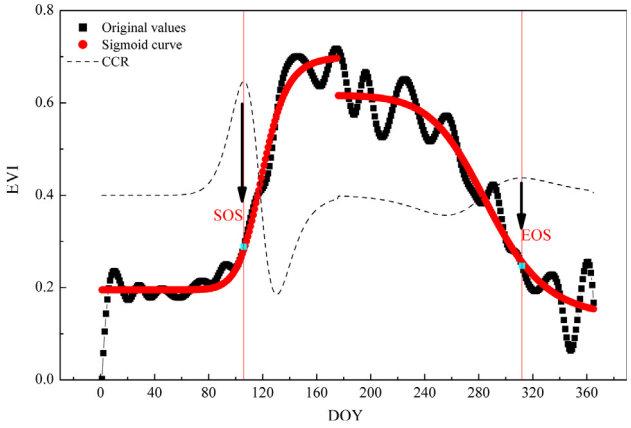

Fig. 1. The schematic diagram of how vegetation phenological information extracted from time-series EVI. Two marked points represent SOS and EOS, respectively. DOY–Day of year.

2. Methods and materials

2.1. Site description

The flux site (US-Moz) is located in the University of Missouri Baskett Wildlife Research area, situated in the Ozark region of central Missouri (Lat. 38°44′39″N, Long. 92°12′ W, Elev. 219 m), which represents an ecologically important transitional zone between the central hardwood area and the grassland region of the US. The tower is placed in the temperate deciduous forest under the joint support from Oak Ridge National Laboratory and the U.S. Department of Energy. Climate of the area is characterized as warm, humid, and continental, with monthly mean temperature of 1.3 °C in January and 25.2 °C in July and multi-year mean precipitation of 1083 mm. Second-growth upland oak–hickory forests constitute the major vegetation type at the region, and the major tree species encompass white, post and black oaks (*Quercus alba* L., *Q. stellata* Wangenh., *Q. velutina* Lam.), shagbark hickory (*Carya ovata* (Mill.) K. Koch), sugar maple (*Acer saccharum* Marsh.), and eastern red cedar (*Juniperus virginiana* L.). The peak leaf area index (LAI) is approximately 3.7 in summer (Seco et al., 2015). Leaf emergence typically occurs in late March and early April, and leaf fall is completed by November. The two dominant soil types in the site are Weller silt loam (fine, smectitic, mesic Aquertic Chromic Hapludalf) and Clinkenbeard very flaggy clay loam (clayey-skeletal, mixed, superactive, mesic Typic Argiudoll) (Young et al., 2001). Additional details about the site are presented in the study of Gu et al. (2015).

2.2. Flux data processing

At present, long-term measurements of CO_2 and water vapor fluxes were conducted through eddy covariance (EC) technique across varied ecosystems on Earth for quantitative and direct evaluation of the potential impacts of climate anomalies on terrestrial carbon dynamics (Goulden et al., 1996; Law et al., 2002). As a member of the AmeriFlux network, the site has been operational since 2004. Flux data and meteorological observations were collected continuously up to 2015 from a 32 m walkup scaffold tower, located at approximately 10 m above the top canopy. A total of 11 years of flux measurements from 2005 to 2015 were used for analysis because of the incomplete data in 2004. CO_2 and water fluxes were recorded using an EC system consisting of a 3D ultrasonic anemometer (CSAT3, Campbell Scientific, Logan UT, USA) and a fast response, open-path infrared CO_2/H_2O gas analyzer (LI7500A, Li-Cor, Lincoln NE, USA). The anemometer and gas analyzer were installed on the top of the tower and all sampled at 10 Hz. The eddy fluxes were processed at a half-hourly time scale.

A series of software programs were used for post-processing

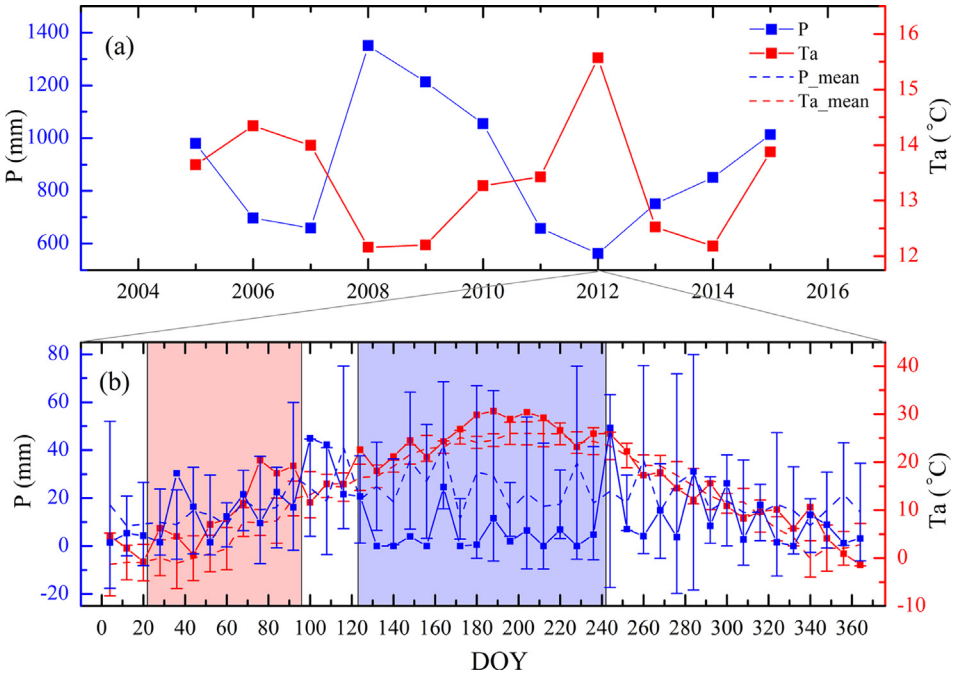

Fig. 2. (a) Annual mean air temperature (T_a) and precipitation (P) from 2005 to 2015 at the forest site. (b) Seasonal variations in 8-day precipitation and air temperature during the extremely dry year of 2012. The pink and blue columns represent the periods of spring temperature anomaly and summer drought in 2012, respectively. Error bars represent one standard error. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

analysis. Data collection and regular calibrations of the tower-based flux measurements were completed as described by Ruehr et al. (2012). The data were quality checked, and data gaps due to system failure or data rejection were gap-filled using standardized methods (Papale et al., 2006; Tang et al., 2017) to obtain complete and standardized data sets. The measured NEE data were partitioned into its two components, namely, GPP and Re through nonlinear regressions with air/soil temperature (Desai et al., 2008). In this study, the night-time based flux-partitioning algorithm proposed by Reichstein et al. (2005) was applied for separation. This method derives a short-term temperature response of Re from the eddy covariance data based on the Lloyd and Taylor (1994) regression model and then applies this relationship to the extrapolation from night-time to daytime Re. Performance of the partitioning methodology was assessed by Stoy et al. (2006). Eventually, this algorithm yields less-biased estimates of GPP and Re (Papale et al., 2006; Tang et al., 2015). The missing values can be gap-filled because of the covariance between flux measurements and meteorological driving factors. All of these works including gap-filling and flux partitioning are completed using the R-based package proposed by the Max Planck Institute for Biogeochemistry (https://www.bgc-jena.mpg.de/REddyProc/brew/REddyProc.rhtml).

Ecosystem WUE is generally defined as the ratio of GPP to ET (Beer et al., 2009; Niu et al., 2011b). We used the daily WUE (g CO_2 kg^{-1} H_2O) to denote the seasonal dynamics of forest response to climate change. Given active photosynthetic activity occurred only for days during the growing season, we applied a filter to exclude daily GPP and ET values when mean daily latent heat flux (LE) < 20 W/m^2, global radiation (Rg) < 150 W/m^2 and mean air temperature (Ta) < 0 °C. The measured LE fluxes were used to calculate water loss (ET, mm d^{-1}) by multiplying a factor of 0.035 which was converted by ET = LE/λ (where λ is amount of evaporation energy per unit weight of water with 2454000 J kg^{-1}) (Tang et al., 2014, 2017).

2.3. Vegetation phenology from MODIS data

The primary data source used to extract the key vegetation phenological information is the enhanced vegetation index (EVI), which we calculate using the site-level data from the MODIS BRDF/albedo product (Schaaf et al., 2002). In particular, the nadir BRDF-adjusted reflectance daily L3 data (MCD43A4, V006) has experienced view angle effects removed, and both cloud and aerosol contamination minimized. The MCD43A4 product provides the reflectance of MODIS bands 1–7 adjusted at a spatial resolution of 500 m by using the bidirectional reflectance distribution function to model the values from the nadir view (https://modis.ornl.gov/). The red, near-infrared and blue bands were used to compute EVI (Huete et al., 2002) as follows:

$$EVI = 2.5\left[\frac{\rho_{NIR}-\rho_R}{\rho_{NIR} + 6\rho_R - 7.5\rho_B + 1}\right]$$

where ρ_{NIR}, ρ_R and ρ_B are the spectral reflectance in MODIS bands 2, 1 and 3, respectively.

Time-series EVI data must be preprocessed to extract vegetation phenology because they include gaps due to clouds and are inherently noisy. In this regard, the missing data were replaced using a moving-window average based on the nearest available data (i.e., linear interpolation). For a single growth or senescence cycle, the EVI data were fitted using sigmoid functions of time, whereas the phenological transition dates were identified based on the curvature-change rate (CCR) of the fitted logistic models at each pixel. This method characterizes key phenological phases by using four transition dates, two of which are of interest in the present study, namely, 1) green-up, the date of onset of EVI increase; and 2) dormancy: the date of onset of EVI minimum. We used SOS, EOS and LOS to represent the start, end and length of the growing season (D'Odorico et al., 2015), respectively. Specifically, the transition dates correspond to the time when the CCR exhibits a local minima or maxima. During SOS, the maximum CCR value corresponds to the onset of greenness increase, whereas during EOS, the maximum CCR value represents the end of greenness decrease. Fig. 1 showed the schematic diagram of how vegetation phenological information extracted from time-series EVI data in 2014. To reveal the effects of climate anomaly on vegetation phenology at the temperate forest site, 11 years of time-series MODIS EVI data from 2005 to 2015 were computed for obtaining the key phenological information including SOS, EOS and LOS.

3. Results

3.1. Identification of climatic anomalies

During the 11-year measurement period at the humid temperate

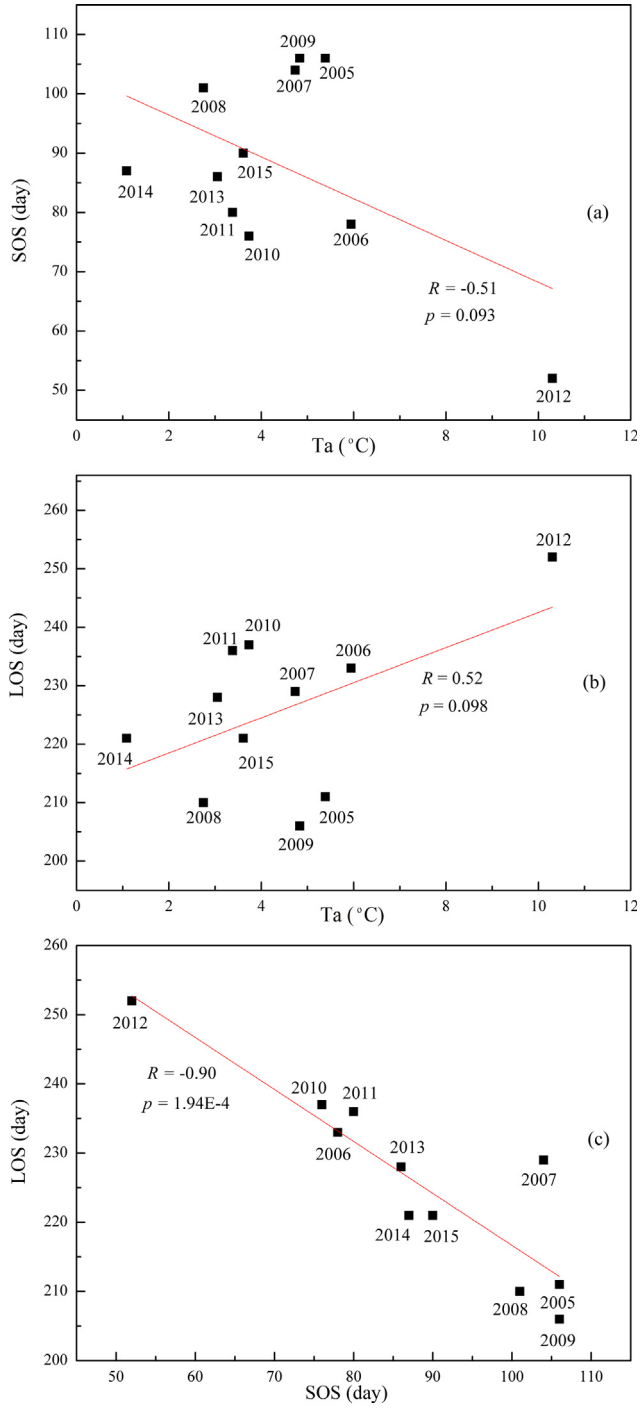

Fig. 3. Relationships between the start (a) and length (b) of the growing season, and mean air temperature during the spring temperature anomaly in 2012, as well as the relationship between SOS and LOS (c) from 2005 to 2015. *P* means the significance level.

forest site, the multi-year mean annual temperature and precipitation were 12.11 °C and 986 mm, respectively. By contrast, Fig. 2a revealed that an extremely dry year–2012 occurred with the highest temperature of 15.57 °C and the fewest amount of precipitation approximately 563 mm in total, highlighting the severity of the extreme weather events. Meanwhile, more details about the climatic anomaly during 2012 were compared with the other years on the basis of 8-day mean temperature and precipitation. The amounts of precipitation in summer 2012 over many 8-day periods were close and even beyond to the normal lower limit of multi-year mean values. Fig. 2b implied the extremely dry 2012 was mainly ascribed to the coincidence of summer heatwave and drought, almost no rainfall around the period of DOY 123 and 242. Moreover, the seasonal anomaly of spring temperature (DOY 22 and 96) is apparently higher than the multi-year mean value between 2005 and 2015. Fig. 2b implied that most 8-day mean temperature values during springtime 2012 were beyond the extent of ± 1 standard error.

3.2. Impact of spring temperature anomaly on phenology

Climate changes, particularly temperature anomaly in springtime, generally control the shifts in the vegetation phenology and the annual carbon uptake period. Therefore, changes in phenological phases, including SOS and LOS, are crucial to understand terrestrial carbon sequestration. In this study, linear regression was performed to evaluate the potential influence of spring temperature anomaly on vegetation phenology. Based on the 11-year measurement, Fig. 3a revealed a strong negative correlation between SOS and springtime Ta. In spite that the *P* value is significant at 0.1 level, the regression analysis implied that SOS can be advanced by approximately 3.5 days per °C with increasing Ta in a certain extent. Thus, the high temperature in springtime stimulated the early green-up of plants. LOS was strongly and positively correlated to springtime Ta. The period of LOS was elongated with about 3 days per °C, and reached the peak in 2012. The correlation coefficients of SOS and LOS with spring temperature were −0.51 and 0.52, respectively. Fig. 3c showed a markedly strong negative correlation between SOS and LOS during the 11-years measurements. The linear regression is significant at 0.05 level (*P* value). Therefore, the earlier SOS, the longer LOS.

3.3. Response of carbon fluxes to climate anomalies

The seasonal dynamics of daily NEE in the humid temperate forest during 2005–2015 were depicted in Fig. 4, which exhibited a typical V-like curve over these years. In the summertime, the forest site generally acted as a strong carbon sink for the benefit of carbon cycle, but released CO_2 from the biosphere to the atmosphere during the non-growing season. Moreover, the multi-year mean daily NEE variations in Fig. 4 made the trend more characteristic. By contrast, the starting date of the carbon sink in 2012 was advanced by nearly 40 days owing to springtime temperature anomaly. The growing season of 2012 started at DOY 52, with the carbon offset at about DOY 97. Nevertheless, the forest changed from carbon sink to source at approximately DOY 180 during the peak growing season. The abnormal dynamics in NEE can be explained by the extremely dry summer in 2012, which increasingly aggravated the water scarcity around this period. Fig. 5 confirmed that NEE of the 2012 summer was the weakest among the 11 years. Overall, the annual mean NEE in 2012 performed as a weak carbon sink with about -0.28 g CO_2 m^{-2} d^{-1} in comparison with the multi-year mean value of -0.78 g CO_2 m^{-2} d^{-1}. Therefore, the severe summer drought significantly reduced the forest carbon sequestration capacity.

Fig. 6 further explained the NEE dynamics during the periods of spring temperature anomaly and summer drought in 2012 from the perspective of GPP and Re components. Interestingly, both GPP and Re co-varied with a consistent tendency, and the annual mean values hit bottom in 2012. As illustrated in Fig. 5, the weakest NEE during the 2012 summer drought was mainly dominated by the sharp reduction in GPP rather than Re. The multi-year mean GPP and Re during this period of 2005 to 2015 were 8.78 g CO_2 m^{-2} d^{-1} and 5.56 g CO_2 m^{-2} d^{-1}, respectively, in spite of 5.15 g CO_2 m^{-2} d^{-1} and 3.33 g CO_2 m^{-2} d^{-1} in 2012 summer. Influenced by the spring temperature anomaly in 2012, the GPP displayed a smaller increase compared with that in the other years. By contrast, the Re was markedly increased, making the NEE value reach its peak in the springtime of 2012.

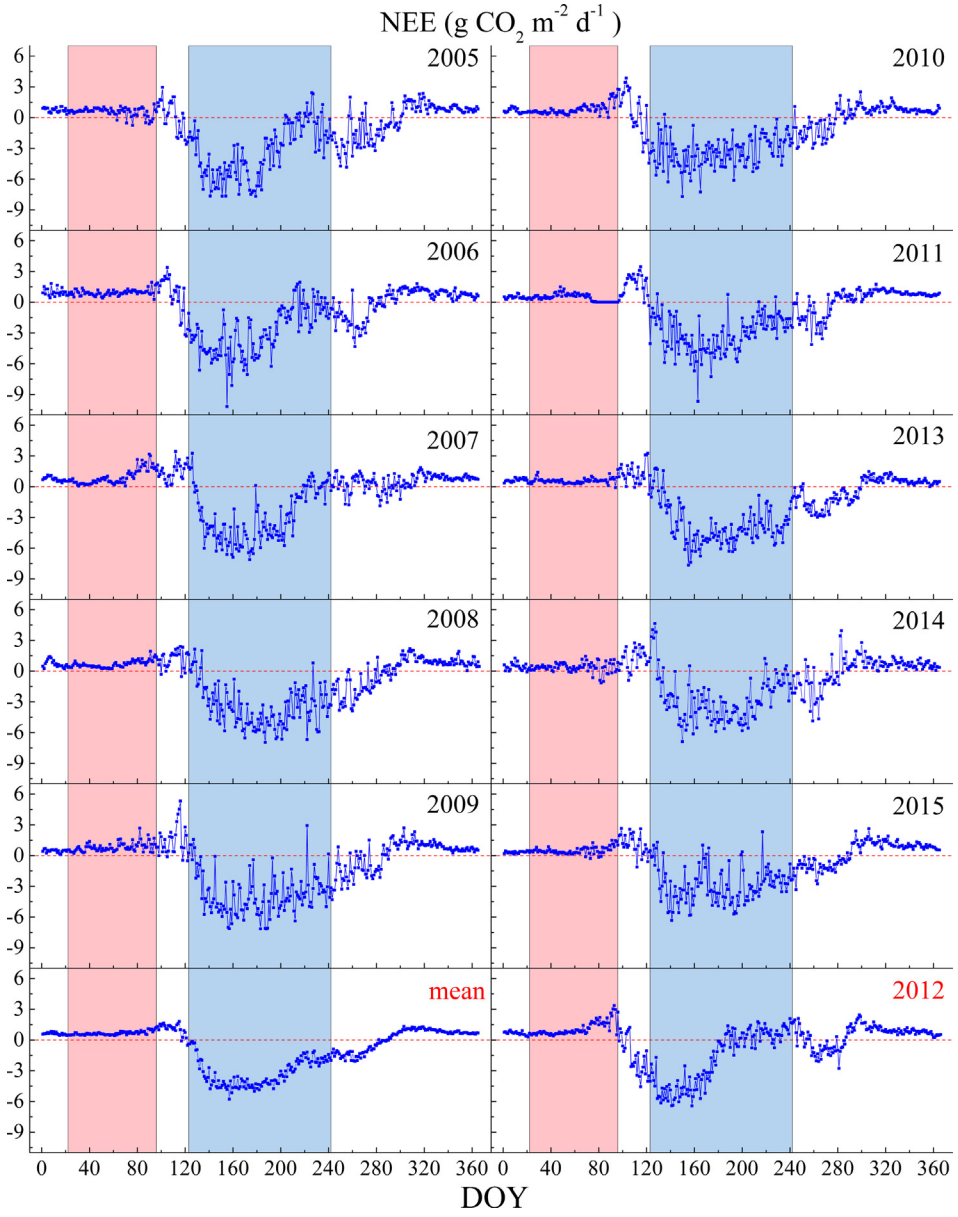

Fig. 4. Daily dynamics and multi-year mean values of NEE during 2005–2015 at the humid temperate forest site.

3.4. Potential effects on ecosystem WUE

Fig. 5 showed that the carbon sequestration capacity was strong before the extremely dry 2012 with -3.16 g CO_2 m^{-2} d^{-1} and recovered quickly after this event with -3.73 g CO_2 m^{-2} d^{-1}, where the NEE was -1.82 g CO_2 m^{-2} d^{-1} in 2012. As an important linkage between terrestrial carbon and water cycles, the effects of ecosystem WUE to such climate anomalies remained unclear in the temperate forest site. Thus, daily dynamics of GPP, ET and ecosystem WUE among the three years were depicted to exhibit how they responded to the spring temperature anomaly and summer drought in 2012 (Fig. 7). In particular, owing to the earlier SOS in 2012, both GPP and ET were apparently higher than those in the adjacent years 2011 and 2013 (Table 1). Meanwhile, the forest maintained a strong ecosystem WUE in the period. But during the peak growing season (summer), the long-term water scarcity sharply decreased ecosystem WUE, resulting in the lowest GPP and ET. During the dry period in 2012, GPP decreased by 34.1% in comparison with 2011, whereas ET had a slighter reduction with 28.1%. Therefore, such event reduced GPP more than ET which led to the decreased WUE. Large variability in GPP, ET and ecosystem WUE during the three years implied the strong inherent resilience of the region against climate change.

4. Discussion

4.1. Climate change and vegetation phenology

Climate change and vegetation phenology generally regulated the variation in annual NEE, which indicated that thermal conditions at the onset of the growing season were critical for triggering the emergence of leaves (Ma et al., 2007; Marcolla et al., 2011), and much more important than water status in determining the carbon assimilation capacity of the ecosystem (Groendahl et al., 2007; Barichivich et al., 2013). The responses of vegetation phenology to climate extremes, however, are complicated with varied magnitude along climatic gradients and among biomes (Ma et al., 2015). Several studies reported that early green-up could increase photosynthesis more than respiration among high-latitude biomes in the Northern Hemisphere (Kato et al., 2006; Piao et al., 2011). However, this study found that at the humid temperate forest site Re increased more than GPP during the springtime

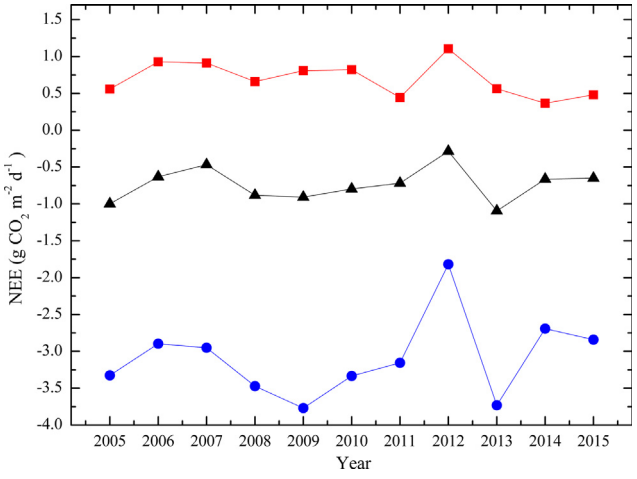

Fig. 5. Inter-annual dynamics in NEE during spring temperature anomaly (red line) and summer drought (blue line) in 2012, and the annual means (black line) from 2005 to 2015. These NEE values are also illustrated in Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

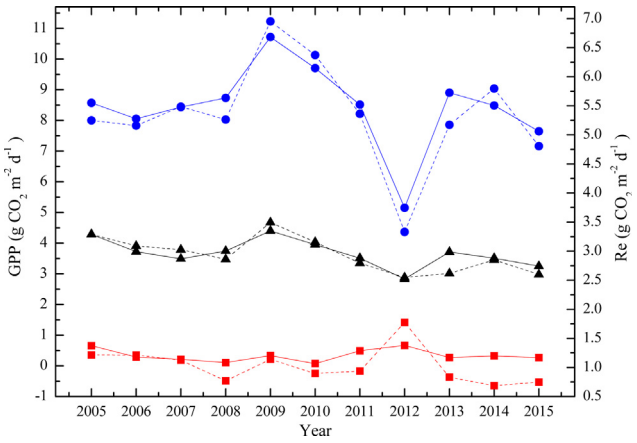

Fig. 6. Inter-annual variations in GPP and Re during spring temperature anomaly (red line) and summer drought (blue line) in 2012, as well as the annual means (black line) from 2005 to 2015. The solid and dotted lines represent GPP and Re, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 6), and acted as a stronger carbon source in this period (Fig. 5). Numerous studies have documented advances in the timing of spring onset in temperate vegetation areas across the Northern Hemisphere (Schwartz et al., 2006; Monahan et al., 2016). These trends are unequivocally attributed to spring warming. Combined with the advances in spring onset, the delays in autumn senescence have extended the growing season length in Eurasian and North American temperate forests over the past years (Menzel et al., 2008; Jeong et al., 2011; Liu et al., 2016). The continuing trends of rising air temperatures in temperate region suggest increasingly earlier spring leaf-out, which is potentially tempered by photoperiod or chilling requirements in certain species, delayed senescence, and consequently longer growing period. The study also implied that SOS was strongly and negatively correlated to LOS, which meant that the earlier SOS, the longer LOS (Fig. 3c). In spite that terrestrial ecosystems generally have recurrent phenological cycles driven predominantly by temperature variability, vegetation growth can be nearly completely inhibited under the extreme drought in spring (Ma et al., 2015). But when the favorable period arrived, vegetation maintained the ability to recover and grow.

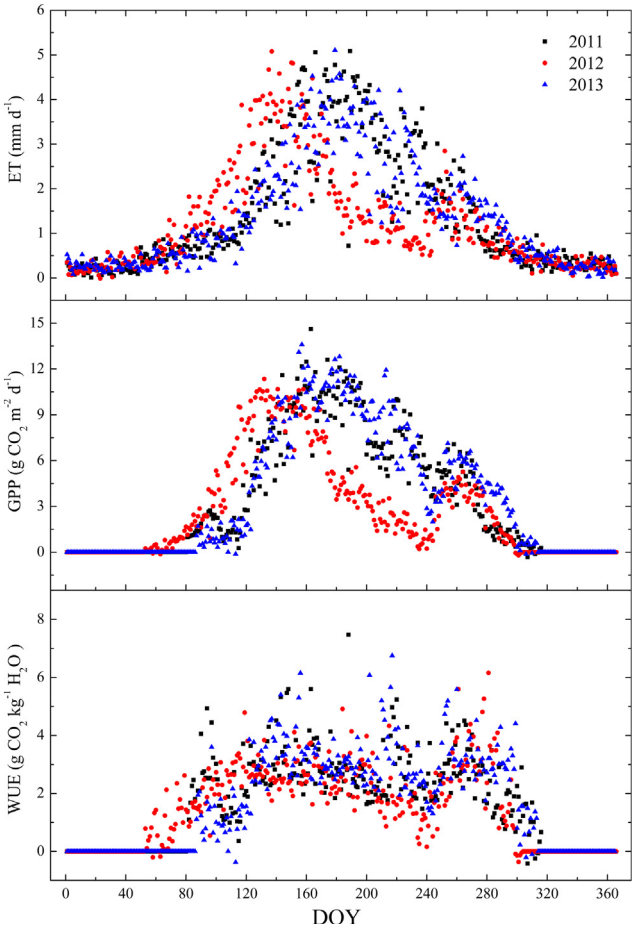

Fig. 7. Daily dynamics of GPP, ET and ecosystems WUE during the adjacent years of 2012.

Table 1
Mean GPP, ET and ecosystem WUE in 2011, 2012 and 2013 during the spring temperature anomaly and extremely dry period in 2012, and the entire year.

Year	Spring temperature anomaly			Extreme dry period			The entire year		
	ET	GPP	WUE	ET	GPP	WUE	ET	GPP	WUE
2011	0.46	0.49	0.90	3.10	8.32	2.90	1.46	3.51	1.75
2012	0.65	0.67	0.89	2.23	5.48	2.39	1.27	2.83	1.70
2013	0.43	0.27	0.66	2.83	8.61	3.17	1.41	3.71	1.86

Note: The unites of GPP, ET and WUE are $g\,CO_2\,m^{-2}\,d^{-1}$, $mm\,d^{-1}$ and $g\,CO_2\,kg^{-1}\,H_2O$, respectively.

4.2. Climate controls on forest carbon sequestration

Amplification of the hydrological cycle as a consequence of global climate warming increases the frequency, intensity, and spatial extent of extreme climate events globally (Sheffield and Wood, 2008). The effects of such events on ecosystem functions, particularly on terrestrial carbon budget remain largely uncertain. Barr et al. (2007) found that when a boreal aspen forest received adequate precipitation, the annual GPP was largely controlled by how long the deciduous canopy had leaves, as this governed the amount of solar radiation that was intercepted. However, the photosynthetic light-use efficiency was diminished under drought conditions, although the canopy's capacity for light interception was unchanged (Gitelson et al., 2015). The potential carbon sequestration of a forest can be influenced by a range of climatic variables such as energy and water through their impacts on GPP and

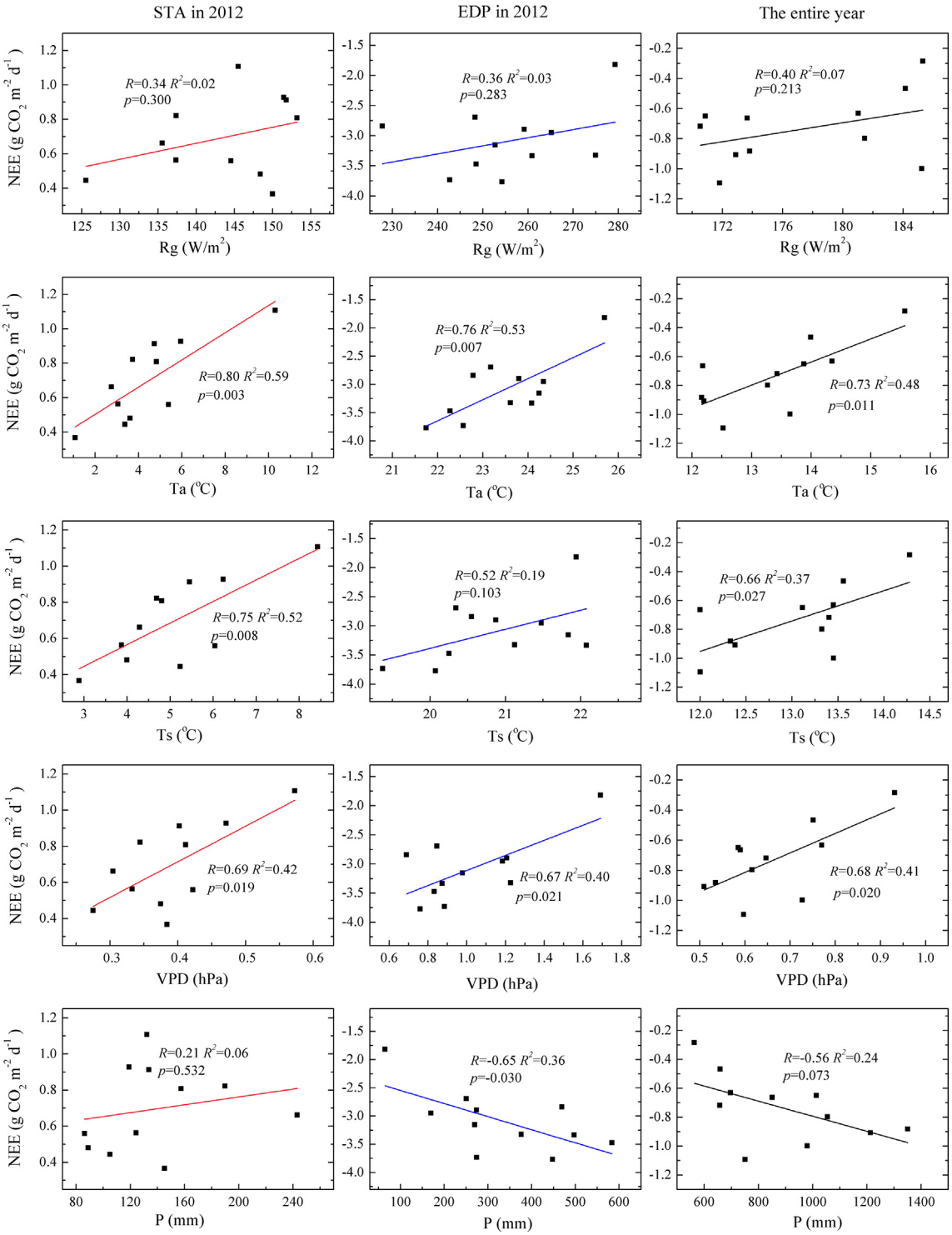

Fig. 8. The relationship between NEE and solar radiation (Rg), air temperature (Ta), soil temperature (Ts), vapor pressure deficit (VPD), precipitation (P) during the spring temperature anomaly (STA) and extremely dry period (EDP) in 2012, as well as the entire year. *P* means the significance level.

Re (Wilhite, 2016). The responses to drought of annual NEE and its components might spatially and temporally change depending on the severity, continuation and timing of the droughts (Mitchell et al., 2015; Schlesinger et al., 2016). Generally, GPP is majorly affected by droughts during the growing season, whereas Re could be influenced by droughts occurring throughout all seasons. Although drought is generally associated with declines in forest carbon sequestration due to water and heat stresses on ecosystem metabolism (Eamus et al., 2013), the magnitude of reduction, which is determined by ecosystem sensitivity to drought, varies dramatically across or even within biomes (Knapp et al., 2015). Our current knowledge on these responses remains limited, a comprehensive understanding of the factors that determine the variations in sensitivity to drought across terrestrial biomes is crucial.

Linear regression was used to examine the environmental controls on the carbon sequestration potential at the humid temperate deciduous forest (Fig. 8). The relationships were analyzed at three periods, namely, the spring temperature anomaly (STA) and extremely dry summer (EDP) in 2012, and the annual time scale over the 11 years of

Table 2
Correlations among GPP, ET and ecosystem WUE with the associated environmental controlling factors during the three periods from 2005 to 2015.

	Period	Rg	Ta	Ts	VPD	P
GPP	Spring temperature anomaly	−0.27	0.64*	0.66*	0.46	−0.21
	Extreme dry period	−0.23	−0.66*	−0.31	−0.68*	0.63*
	The entire year	−0.07	−0.61*	−0.41	−0.56	0.60*
ET	Spring temperature anomaly	0.12	0.88**	0.86**	0.63*	−0.09
	Extreme dry period	−0.32	−0.58	−0.11	−0.69*	0.88**
	The entire year	−0.05	−0.35	−0.13	−0.53	0.82**
WUE	Spring temperature anomaly	−0.38	0.47	0.52	0.30	−0.25
	Extreme dry period	0.08	−0.15	−0.37	−0.04	−0.38
	The entire year	−0.06	−0.27	−0.35	0.05	−0.45

Note: ** and * mean that the correlation coefficients are significant at 0.01 and 0.05 level, respectively.

measurements. The study found that: 1) all climate factors including solar radiation (Rg), air temperature (Ta), soil temperature (Ts), vapor pressure deficit (VPD) and natural precipitation (P) performed consistent trends during EDP and annual periods, which indicated that the growing season acted as the most important role around the year for a ecosystem; 2) with the increases in Rg, Ta and Ts, and VPD across the three periods, the capacity of carbon sequestration weakened, implying that they were not the dominant factors in the region; 3) only P exhibited distinctly different correlations during the STA and EDP periods. More rainfall in springtime led to a slight decrease in NEP, whereas the NEP was positively correlated with P during the summertime. This finding again demonstrated that the amount of rainfall dominantly controlled the carbon fixation capacity. Therefore, in summer 2012, not only the heatwave, but also the drought exerted extremely adverse effects on the humid temperate deciduous forest.

4.3. Responses of ecosystem WUE to climate factors

Previous studies showed that the cumulative effect of the spring temperature was the principal limiting factor in breaking plant dormancy, leaf phenological development, and subsequent plant growth (Kato et al., 2006; Marcolla et al., 2011; Shen et al., 2015). The strong correlations between GPP, Ta and Ts during the spring temperature anomaly reached up to 0.64 and 0.66, respectively (Table 2). Meanwhile, the water loss (ET) exhibited a much stronger relationship with Ta and Ts. Nevertheless, during the peak growing season, the high Ta and Ts turned into a negative controlling factor for GPP and ET. But natural rainfall (P) was positively and strongly correlated to GPP and ET, with coefficients of 0.63 and 0.88, respectively. It implied that both GPP and ET would suffer from the constraints of water scarcity, in spite that WUE did not decrease significantly as the ratio of GPP to ET on the annual time scale (1.75 g CO_2 kg^{-1} H_2O in 2011 *vs* 1.70 g CO_2 kg^{-1} H_2O in 2012). But the heatwave in summer 2012 further amplified the effect of drought on forest GPP and ET, and led to the decreased WUE (2.39 g CO_2 kg^{-1} H_2O) compared with the adjacent years during the extreme dry period (2.90 g CO_2 kg^{-1} H_2O in 2011 and 3.17 g CO_2 kg^{-1} H_2O in 2013). Dynamics in ecosystem WUE were affected by a series of variables, including CO_2 levels (Keenan et al., 2013), water vapor pressure deficit (Yang et al., 2010; Mitchell et al., 2015), solar radiation (Rocha et al., 2004; Gitelson et al., 2015), and human-induced disturbances (Magnani et al., 2007; Tang et al., 2017). The dominant controls varied among sites and across scales. The response of an ecosystem's WUE to climate anomalies remain a difficult challenge, and more studies are needed to set up the common principles that govern it.

5. Conclusions

In spite that the EC-based measurements of CO_2 and H_2O fluxes at the humid temperate forest only had 11 years of data, and the flux partitioning method for GPP and Re components owned plenty of uncertainties, this study revealed that climate extremes have exerted dramatic impacts on vegetation phenology, carbon sequestration and ecosystem WUE. The main findings were summarized as follows. 1) Green-up dates were advanced with the increase in spring temperature (approximately 3.5 days per °C in SOS). Meanwhile, the growing season (LOS) elongated apparently with about 3 days per °C, and reached the peak at 2012. 2) The shift of carbon source to sink in 2012 advanced by nearly 40 days owing to springtime temperature anomaly. However, the extremely dry summer severely reduced forest carbon sequestration capacity from 0.78 g CO_2 $m^{-2}d^{-1}$ to 0.28 g CO_2 $m^{-2}d^{-1}$. Further analyses implied that the weakest NEP was mainly dominated by the sharp reduction in GPP rather than Re. 3) In view of earlier SOS in 2012, both GPP and ET were apparently higher than those during the adjacent years. But prolonged summer drought sharply decreased the ecosystem WUE, resulting in the fewest GPP and ET. 4) In this area, the amount of precipitation dominantly controlled the capacity of forest carbon sequestration. The heatwave together with summer drought exerted extremely adverse effects in 2012. All of these findings provide important implications for developing forest adaption strategies to mitigate future climate changes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jhydrol.2018.08.012. These data include Google maps of the most important areas described in this article.

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